

**NON-VOLATILE, HIGH DENSITY, HIGH SPEED,  
MICROMAGNET-HALL EFFECT RANDOM ACCESS MEMORY (MHRAM)**

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**ABSTRACT**

The micromagnet-Hall effect random access memory (MHRAM) has the potential of replacing ROMs, EPROMs, EEPROMs and SRAMs because of its ability to achieve non-volatility, radiation hardness, high density, and fast access times, simultaneously. Information is stored magnetically in small magnetic elements (micromagnets), allowing unlimited data retention time, unlimited numbers of rewrite cycles, and inherent radiation hardness and SEU immunity, making the MHRAM suitable for ground based as well as spaceflight applications. The MHRAM device design is not affected by areal property fluctuations in the micromagnet, so that high operating margins and high yield can be achieved in large-scale IC fabrication. The MHRAM has short access times ( $<100$  nsec). Write access time is short because on-chip transistors are used to gate current quickly, and magnetization reversal in the micromagnet can occur in a few nanoseconds. Read access time is short because the high electron mobility Hall sensor (InAs or InSb) produces a large signal voltage in response to the fringing magnetic field from the micromagnet. High storage density is achieved since a unit cell consists only of two transistors and one micromagnet-Hall effect (M-H) element. By comparison, a DRAM unit cell has one transistor and one capacitor, and an SRAM unit cell has six transistors.

**INTRODUCTION**

Ever increasing data processing requirements demand faster and denser random access memory (RAM) to keep pace with improved CPU speed and throughput. Nonvolatility becomes an important factor in many applications where reliability, fault tolerance and fault recoverability, and low power consumption are necessary. Semiconductor memories such as dynamic RAM and static RAM (DRAM and SRAM) have very fast access times, but are volatile, and batteries which could provide backup power are considered risky, unreliable, and consume mass and volume<sup>1</sup>. EEPROMs are non-volatile, but have very long write times (on the order of msec), limited endurance ( $10^4$  to  $10^6$  write cycles), and require compromises between refresh needs and radiation tolerance. Shadow SRAMs, which have a regular SRAM cell and an EEPROM cell in each memory cell, are costly and still suffer from the endurance problem of the EEPROM. Ferroelectric RAM (FRAM) offers short read and write access times, but the data retention (nonvolatility) and the longevity of the ferroelectric material (reliability) are in question. The magneto-resistive random access memory (MRAM<sup>2</sup>) is non-volatile and has no problem with longevity, but has long read access times (on the order of microseconds).

No existing nonvolatile RAM technology satisfies each of the needed data storage requirements. A summary of the performance of these technologies, including the 256 Kbit and 1 Mbit versions of the proposed MHRAM<sup>3</sup>, is given in Table 1. It is seen in Table 1 that MRAM and MHRAM come the closest to being the most reliable and truly nonvolatile memories. The proposed MHRAM uses a novel scheme to achieve short read access time while retaining the other merits of the MRAM. The MHRAM therefore has the potential to replace SRAMs and all types of ROMs, including PROMs, EPROMs, UVROMs and EEPROMs.

## POTENTIAL APPLICATIONS

### Low Cost, High Performance Replacement for EPROMs and EEPROMs

To write to EPROMs and EEPROMs, a voltage higher than 5 V is usually needed. Special circuit and programming sequence are needed for the write function. The write operation may take from milliseconds to seconds. During these times, the memory content can not be read. Therefore, the write operation is usually done with operator intervention. The reprogramming cost greatly outweighs the cost of the chip. The EPROM and EEPROM can only be reprogrammed for  $10^4$  to  $10^6$  times before permanent damage is done. Thus, the user must minimize and keep track of the number of the write cycles, so that the chip can be replaced periodically. The MHRAM can be treated as a regular SRAM. It can be read and written just like any other main memory, using the same instruction and memory cycle time. There is no need to limit the number of write cycles or replace the chip periodically.

### Memory Card

Flash EEPROM is currently proposed for the memory card to be used in the notebook computer. Flash EEPROM has the same drawbacks as the EEPROM, i.e., long write time and limited number of write cycles. MHRAM can be used to implement a fast access time and unlimited write cycle memory card.

### Solid State Disk

The currently available solid state disks are implemented using SRAM. If non-volatility is required, a battery is used as the backup power. MHRAM can be used to implement a non-volatile solid state disk, which does not need backup power. Solid state disk is typically used as a cache memory between the main memory and the hard magnetic disk. A truly non-volatile solid state disk would relieve the system requirement to backup the content in the solid state disk to the hard disk during power down.

### Main Memory

Using MHRAM to implement the main memory can have a profound effect on the computer system. Since the content of the main memory is not lost after the power is lost, the computer can resume its computation after the power has been reinstalled. There will be no need to use the write-through scheme in managing the memory hierarchy, the more efficient write-back scheme can be used without worrying the loss of data due to power failure. There will be other impacts when such a non-volatile memory is available.

## MHRAM CELL STRUCTURE

A high speed, non-volatile random access memory cell can be achieved by a micromagnet-Hall effect (M-H) element whose structure is shown in Fig. 1. The M-H element consists of a ferromagnetic element (called micromagnet), shown as the right-slanted area, and a Hall effect sensor, shown as the shaded area. The non-volatile storage function is realized with a micromagnet having an in-plane, uniaxial anisotropy, and, very importantly, in-plane, bipolar remanent magnetization states. The information stored in the micromagnet is detected by a Hall effect sensor which senses the fringing field from the micromagnet. As shown in Fig. 1, when

the magnetization in the micromagnet is pointing to the right, a current flowing from lead 3 to lead 4 in the Hall sensor would produce a Hall voltage across leads 1 and 2, with lead 2 being positive with respect to lead 1. When the magnetization in the micromagnet is reversed to point to the left, the same current in the Hall sensor would produce a Hall voltage with the same magnitude but the lead 1 becomes positive. Such a reversal in polarity between the two leads can be detected easily by a differential sense amplifier.

The micromagnet can be magnetized by a local applied field, whose direction is used to form either a "0" or "1" state. The micromagnet remains in the "0" or "1" state until a switching field is applied to change its state, therefore achieving nonvolatility. The micromagnet is magnetized within a few nanoseconds or less, so the write cycle time is very short. The Hall voltage is produced across leads 1 and 2 within a nanosecond. Since this is a differential signal, the settling time of the sense amplifier is short. Both the read and write access times can be within 100 nsec.

## MEMORY ORGANIZATION

One organization for a 2x2 bit MHRAM is shown schematically in Fig. 2. The M-H elements are incorporated in a matrix of gating transistors. Micromagnets are shown as rectangles, and Hall sensors are shown as shaded regions. Consider the cell, MH-21, which occurs at the intersection of the second row and the first column. To read the content of MH-21, signals RS2 (Row Select 2), CS1 (Column Select 1), and Read become high. Transistors Q7, Q9, and Q13 are turned on by RS2, which sends a current through, and produces a Hall voltage at, every Hall sensor in the second row. Each Hall voltage is amplified by a sense amplifier at the corresponding column. However, only transistor Q1 has been turned on (by CS1 AND Read), so that only the signal output from sensor 21 is connected to the final output,  $V_{out}$ . Although transistor Q8 is also turned on when the second row is selected, since none of the transistors Q2, Q3, Q10, and Q11 are turned on, current does not flow through Q8. If a single-output memory organization is desired, the number of sense amplifiers can be reduced to one if the selection transistors (such as Q1) are placed at the input side of the sense amplifier.

To write to cell MH-21, signals RS2, CS1, and Write become high. If the bit value to be written is a "1," then transistors Q3, Q8 and Q11 are turned on, and if the bit value is a "0," then transistors Q2, Q8 and Q10 are turned on. The bit value then decides the sense of the current through the conductor over the magnetic element, and therefore the sense of the in-plane magnetization. It is noted that the switching current amplitude can be set to accommodate the micromagnet with the highest switching threshold among the matrix of micromagnets. This is because the switching field is applied only to the selected micromagnet and, unlike the MRAM and core memory, will not have a half-select problem. Therefore the writing process achieves high margin and is immune to fluctuations in the switching threshold value, caused for example by material variations, so that high chip yields can be achieved.

## READ-OUT SIGNAL LEVEL

One of the critical memory performance parameters is the read-out signal level. The output voltage of the Hall sensor,  $V_{out}$ , is given by:

$$V_{out} = \mu V_x B_z W/L, \quad (1)$$

where  $\mu$  is the Hall electron mobility,  $V_x$  is the voltage drop across the Hall sensor, and W and L are the width and length of the Hall sensor, respectively. It can be seen that the output voltage is proportional to  $\mu$ . Using the value of  $\mu=1 \text{ m}^2/\text{V}\cdot\text{s}$ ,  $B_z = 100 \text{ Oe}$  ( $0.01 \text{ Wb/m}^2$ ), and  $W/L=1$ , Eq. 1 becomes

$$V_{out} = 0.01 V_x, \quad (2)$$

i.e., the output is 10 mV when the voltage across the input is 1 V. If the design goal is to have a 10 mV output voltage, with a 5 V supply, neglecting the voltage drop on the gating transistors, a maximum of 5 Hall sensors

can be connected in series.

## MATERIALS CONSIDERATIONS

### Hall Sensor:

It can be seen from Eq. 1, that the Hall sensor's output voltage is proportional to the electron mobility of the Hall sensor. A high electron mobility material is very desirable. At room temperature, the electron mobility in a single crystal silicon is  $0.13 \text{ m}^2/\text{V-s}$ , which is too low for this application. In a bulk single crystal gallium arsenide (GaAs),  $\mu=0.78 \text{ m}^2/\text{V-s}$ . After doping,  $\mu=0.5 \text{ m}^2/\text{V-s}$ . In a bulk single crystal indium arsenide (InAs),  $\mu=3.3 \text{ m}^2/\text{V-s}$ . In an MBE deposited InAs thin film,  $\mu=1.0 \text{ m}^2/\text{V-s}$ . In a bulk single crystal indium antimonide (InSb),  $\mu=7.8 \text{ m}^2/\text{V-s}$ . In thermally evaporated InSb thin films<sup>4-9</sup>, mobility varies from 0.03 to  $6 \text{ m}^2/\text{V-s}$ , depending on the deposition and annealing conditions. Due to the high cost and low throughput of the MBE, the evaporation and recrystallization process is clearly more practical for mass production.

It is important to note that a 1% variation in the properties of the Hall sensors or the micromagnets throughout the chip only causes a 1% difference in the output voltage. This feature constitutes a significant improvement over the MRAM<sup>2</sup> in which a 1% variation can induce a 50% or 100% variation in output the signal is measured differentially against a fixed reference. Therefore, the MHRAM is expected to be much more insensitive to process variations which occur when manufacturing a large matrix memory.

### Micromagnet:

The criteria for choosing the micromagnet material are that it (1) can be switched relatively easily by a field on the order of 100 Oe to limit on-chip power dissipation and current density, and (2) must have a stable non-zero remanence so that it will remember its magnetization state after the switching field is removed. A larger remanence produces a larger fringing field for the Hall sensor. Permalloy has been shown<sup>10-12</sup> to have a coercivity ranging from 25 to 120 Oe. We have shown that CoPt thin films have coercivity ranging from 100 to 600 Oe.

## CONCLUSION

We have described a scheme using the combination of a micromagnet, Hall sensor, and gating transistors, to achieve a high speed, non-volatile random access memory. Such a memory has the potential to replace ROMs, EPROMs, EEPROMs, and SRAMs. We have studied the base materials needed to implement this memory. Work is currently underway to implement an integrated circuit prototype of such a memory.

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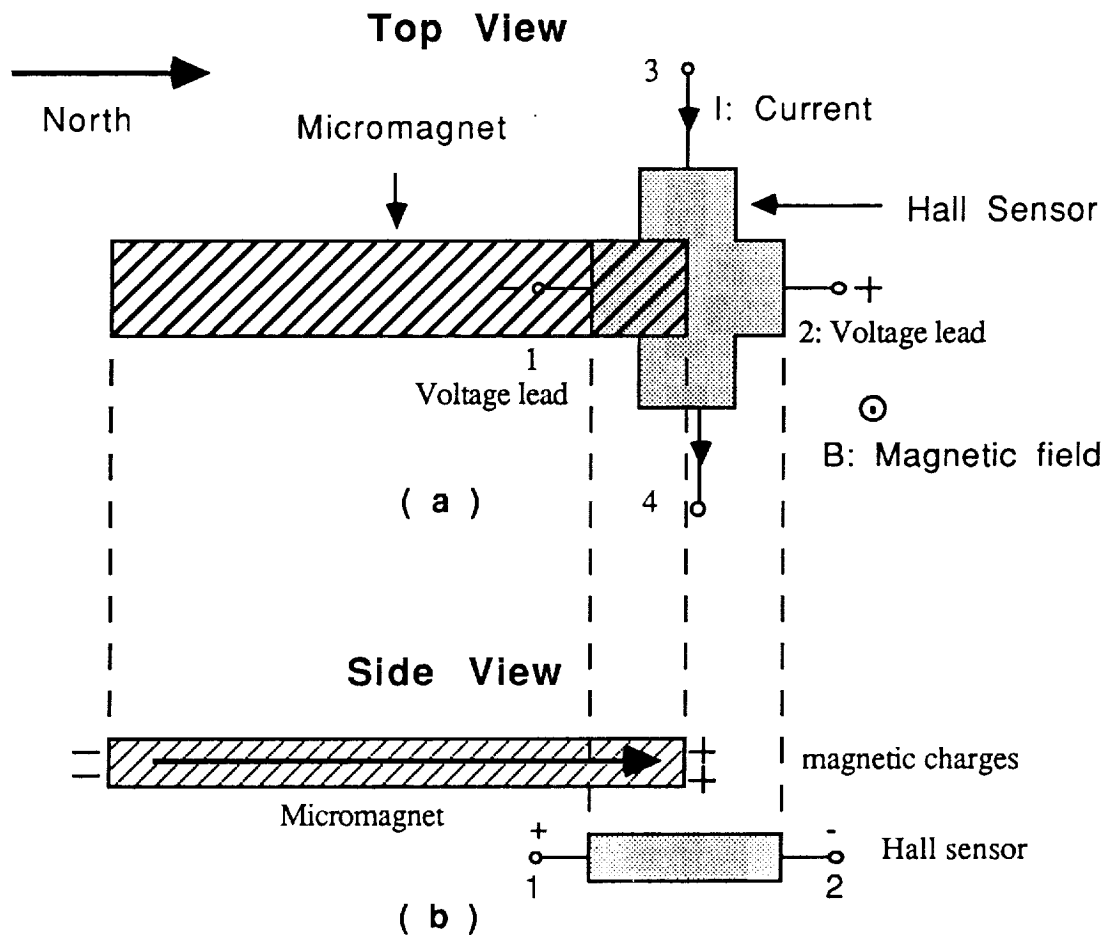
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# Non-Volatile Random Access Memory

Type of Non-volatility	EEPROM	Flash EEPROM	FRAM	MRAM	MHRAM	MHRAM
Sources	Harris Sandia	Intel TI	Krysalis Ramtron	Honeywell	JPL	JPL
Read Cycle Time	200 nsec	150 nsec	200 nsec	1 $\mu$ sec	100 nsec	100 nsec
Write Cycle Time	10 msec	0.4 msec Erase 3 sec	200 nsec	250 nsec	100 nsec	100 nsec
Capacity (bits)	256 K 1 M	256 K 1 M	16 K	16 K	256 K	1 M
Write Power	200 mW	200 mW	150 mW	150 mW	150 mW	200 mW
Read Power	30 mW	30 mW	150 mW	300 mW	150 mW	200 mW
Endurance	$10^4$ to $10^5$ (write)	$10^3$ to $10^4$ (write)	$10^{10}$ to $10^{12}$ (access)	Unlimited	Unlimited	Unlimited
Data Retention	hours - 10 yrs	10 yrs	3 yrs	Unlimited	Unlimited	Unlimited
Total Dose Rad(Si)	5E5	N.A.	1E6	1E6	1E6	1E6
Half-select Problem	N.A.	N.A.	N.A.	Yes	Immune	Immune

Table 1

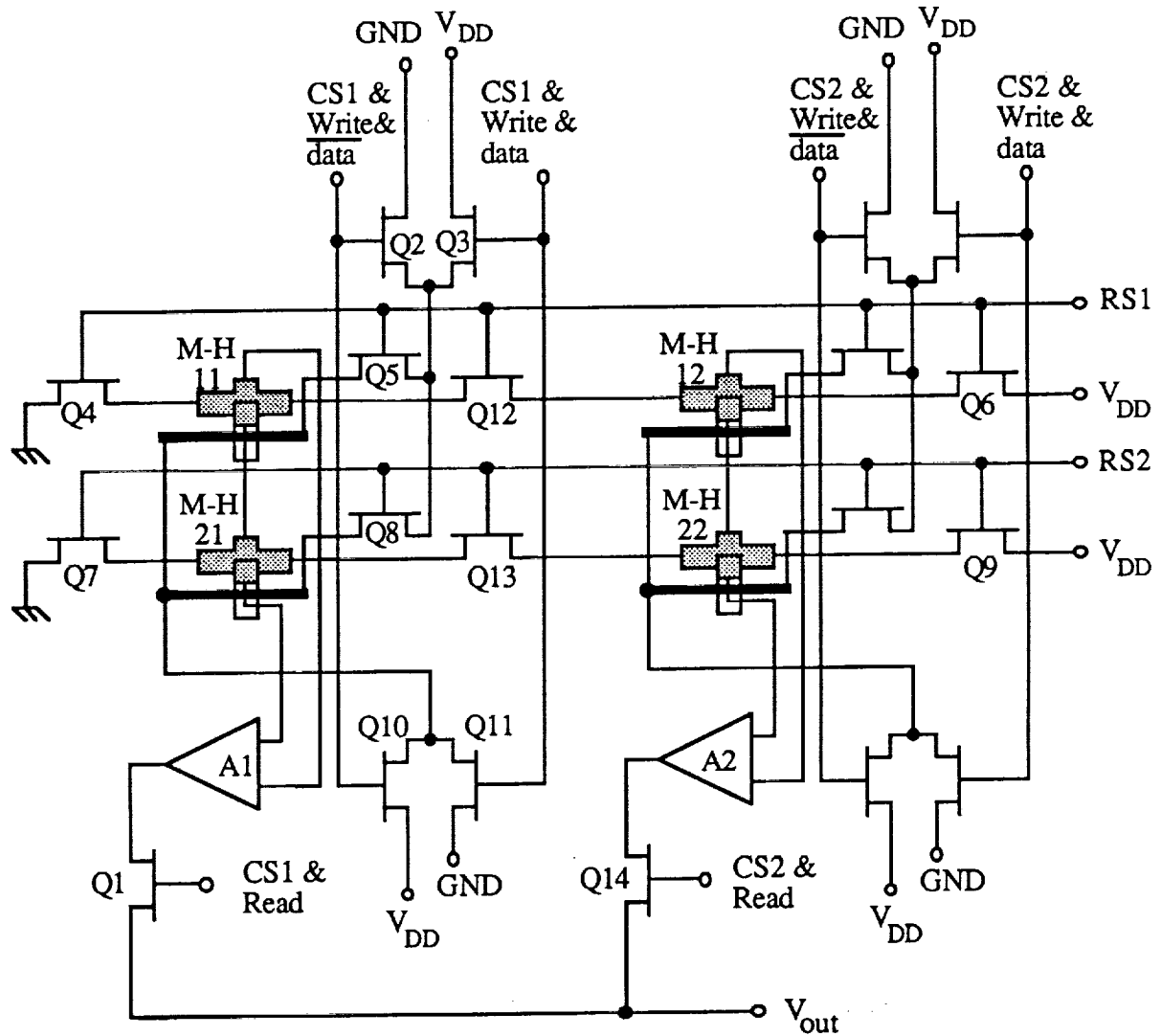
# Hall Effect Sensor with In-plane Micromagnet



- ( a ) In the absence of the magnet, an n-type Hall sensor, when the current is flowing from lead 3 to lead 4 (east), and an external magnetic field is pointing up, a Hall voltage is developed across leads 1 and 2, with lead 1 being negative. The polarity of the Hall voltage changes when the magnetic field direction is reversed.
- ( b ) In the presence of a micromagnet magnetized to the right (north), the Hall sensor experiences a downward field, a Hall voltage is developed with lead 1 being positive. When the micromagnet is magnetized south, the polarity of the Hall voltage reverses.

Figure 1

## A 2x2 bits MHRAM Organization



CS : Column Select    RS : Row Select    M-H : Magnet-Hall effect element

Two transistors and one M-H element in each unit cell

Figure 2